DAVID Y. IGE
GOVERNOR OF HAWAII

SUZANNE D. CASE
CHAIRPERSON

BRUCE S. ANDERSON, PH.D.
WILLIAM D. BALFOUR, JR.
KAMANA BEAMER, PH.D.
MICHAEL G. BUCK
NEIL J. HANNAHS
PAUL J. MEYER

M. Kaleo Manuel
DEPUTY DIRECTOR

STATE OF HAWAII
DEPARTMENT OF LAND AND NATURAL RESOURCES
COMMISSION ON WATER RESOURCE MANAGEMENT
P.O. BOX 621
HONOLULU, HAWAII 96809

STAFF SUBMITTAL

COMMISSION ON WATER RESOURCE MANAGEMENT

March 19, 2019
Honolulu, Hawaiʻi

Authorize the Chairperson to Enter into Joint Funding Agreements with the U.S. Geological Survey to Estimate Ground Water Recharge for Future Climate Conditions for Hawaiʻi

SUMMARY OF REQUEST

That the Commission on Water Resource Management (Commission) authorize the Chairperson to enter into Joint Funding Agreements with the U.S. Geological Survey (USGS) to estimate ground water recharge for future climate conditions for the islands of Kauaʻi, Oʻahu, Molokaʻi, Lānaʻi, Maui, and Hawaiʻi.

BACKGROUND

Climate change is expected to impact water resources in Hawaiʻi in many ways. The best available science indicates that Hawaiʻi will continue to experience changes in rainfall, increasing air and sea surface temperatures, sea level rise, and an increased frequency in extreme events (droughts and flooding). These changes will impact ground water recharge and the availability of ground water supplies, which provide about 90% of Hawaiʻi's drinking water. Although the frequency and geographic distribution of these impacts are uncertain, proactive research is needed to foster adaptive management strategies.

The Hawaii Water Plan requires that the Water Resource Protection Plan (WRPP) establish policies and provide guidance to protect, manage, and conserve the waters of the State. To better inform long-range water planning, the best available information on climate change impacts on ground water recharge is needed.

In the draft update to the WRPP, understanding how climate change will impact water resources is identified as a priority project to meet the Commission's goal of establishing "solid and up-to-date foundation of data on Hawaiʻi water resources, water use, and water dynamics" to make informed water resource management decisions. Now that the statistical approach to climate model downscaling has progressed to the point where it can calculate estimates of rainfall changes at the aquifer system area scale and better represent the microclimates of Hawaiʻi, the Commission staff proposes to partner with the USGS to quantify potential changes in ground water recharge, relative to recent (1978-2007) conditions.

PROPOSED APPROACH

USGS has submitted two separate proposals to quantify potential changes in ground water recharge relative to recent (1978-2007) conditions. The first proposal is for the islands of Kaua'i, O'ahu, Moloka'i, Maui, and Hawai'i. The second proposal is for the island of Lāna'i. A separate proposal is made for Lāna'i because ground water recharge estimates for recent conditions do not exist, and a water budget model must be developed from scratch to incorporate the latest climate datasets and water-budget methods. Therefore, the cost for Lāna'i work is significantly more than that for the other Hawaiian Islands. Due to limitations in funding this fiscal year, the proposal for Lāna'i is broken down into two phases and funding cycles. The proposed work under each proposal is detailed below.

I. Proposal for Kaua'i, O'ahu, Moloka'i, Maui, and Hawai'i Islands

To quantify potential changes in ground water recharge relative to recent conditions for the Hawaiian islands of Kaua'i, O'ahu, Moloka'i, Maui, and Hawai'i, existing ground water recharge estimates will be used, or updated estimates will be developed, for recent conditions (1978–2007), mid-century projected climate conditions (2041 to 2071), and a range (dry and wet) of end-of-century projected climate conditions. Consistent climate datasets and computation methods will be used to enable comparisons among time periods and islands to be made. To control costs, this study will use existing USGS ground water recharge estimates to the extent possible. However, the desire to incorporate critical new information, relevant land-cover conditions, or a consistent computation method may require re-computation of existing estimates. Estimates of future ground water recharge will incorporate published climate projections available at the time this study begins. The proposed study will take 2.5 years to complete.

II. Proposal for the Island of Lāna'i

Primarily, the collection and processing of hydrologic data to create recharge estimates for recent conditions (1978-2007) is required before a comparison of recharge under mid-century and a range of end-of century climate conditions can be accomplished. Estimates of future ground water recharge will incorporate published climate projections for Lāna'i available at the time this study begins. Climate datasets and computation methods consistent with those used for the other main Hawaiian Islands will be used in this study to enable comparisons among time periods and islands to be made. The proposed study will take 2.5 years to complete and is broken down into two phases: Phase I - obtain and process datasets, and Phase II - prepare input files, compute and analyze water budget, publication.

Results of both studies will be documented in USGS Scientific Investigations Reports and associated digital spatial datasets of ground water recharge that will be made available to the public through the internet.

For further detail on the proposed approaches, the full USGS proposals for each study are attached as Exhibits 1 and 2.

LEGAL AUTHORITY

Under its general powers and duties, the Commission has the authority to plan and coordinate programs for the conservation of water and to contract with private persons to assist with these programs. Under section §174C-5 (4), HRS, the Commission "*[m]ay contract and cooperate with the various agencies of the federal government and with state and local administrative and governmental agencies or private persons*". Section §174C-5 (13), HRS, further provides that the Commission "*[s]hall plan and coordinate programs for the development, conservation, protection, control, and regulation of water resources based upon the best available information, and in cooperation with federal agencies, other state agencies, county or other local governmental organizations and other public and private agencies created for the utilization and conservation of water*".

ENVIRONMENTAL REVIEW CHAPTER 343, HAWAII REVISED STATUTES

This planning study is exempt from the application of HRS Chapter 343 pursuant to HRS §343-5(b) and Hawaii Administrative Rule §11-200-5(d). This is for a planning-level study and will not involve testing or other actions that may have a significant impact on the environment.

FUNDING

The total cost to complete both studies is $653,000. The breakdown of funding for each proposal is as follows:

	USGS Contribution	**CWRM Contribution**	**Total**
Future Recharge Estimates for Kaua'i, O'ahu, Moloka'i, Maui, and Hawai'i	$100,000	$233,000	$333,000
Future Recharge Estimates for Lāna'i			
Phase I	$10,000	$40,000	$50,000
Phase II	$86,000	$184,000	$270,000
			$320,000

Funds will be provided through the Commission's general fund, special fund, or a combination of both, subject to available funding.

RECOMMENDATIONS

Staff recommends that the Commission:

1. Authorize the Chairperson to enter into a Joint Funding Agreement with the USGS to develop recharge estimates for future climate conditions for the islands of Kaua'i, O'ahu, Moloka'i, Maui, and Hawai'i, and to expend up to $233,000 for this purpose;

2. Authorize the Chairperson to enter into Joint Funding Agreements with the USGS to develop recharge estimates for future climate conditions for the island of Lāna'i, and to expend up to $40,000 to accomplish Phase I work and $184,000 to accomplish Phase II work.

3. Authorize the Chairperson to amend or modify the Joint Funding Agreements as may be necessary to accomplish the goals described herein, provided that any amendment or modification does not require additional Commission funding; and

4. Find that these planning studies are exempt from the preparation of an environmental assessment under §343-5(b), Hawaii Revised Statutes and §11-200-5(d), Hawaii Administrative Rules.

The terms of these agreements will be subject to the availability of funding and approval of the Attorney General's Office. Contract execution will be done in accordance with Hawaii Revised Statute Chapter 103D and Hawaii Administrative Rules, Chapter 3-122.

Ola i ka wai,

M. KALEO MANUEL
Deputy Director

Exhibits:
1. USGS proposal for Estimating Groundwater Recharge for Future Climate Conditions, State of Hawai'i
2. USGS proposal for Groundwater Recharge for Recent and Future Climate Conditions, Lāna'i, Hawai'i

APPROVED FOR SUBMITTAL:

SUZANNE D. CASE
Chairperson

Estimating Groundwater Recharge for Future Climate Conditions, State of Hawai'i

U.S. Geological Survey
Pacific Islands Water Science Center
Proposal, February 2019

SUMMARY

Projected increases in water demand coupled with projected decreases in rainfall suggest a need for proactive planning and water management in Hawai'i. The Hawai'i Commission on Water Resource Management (CWRM) recognizes the need to improve groundwater recharge estimates to include the best available information on climate-change impacts and to integrate the best available information on the impacts of climate change on long-range water resources planning. Estimates of future groundwater recharge based on published climate projections will enable CWRM to evaluate how groundwater availability may be affected by climate change over a water-resources planning horizon and potentially adjust sustainable-yield values.

The overall objective of this proposed study is to quantify potential changes in groundwater recharge, relative to recent (baseline) conditions, for the Hawaiian Islands of Kaua'i, O'ahu, Moloka'i, Maui, and Hawai'i. To quantify these changes, existing groundwater-recharge estimates will be used, or updated estimates will be developed, for recent conditions (1978–2007), mid-century projected climate conditions, and a range (dry and wet) of end-of-century projected climate conditions. Consistent climate datasets and computation methods will be used to enable comparisons among time periods and islands to be made. To control costs, this study will use existing U.S. Geological Survey (USGS) groundwater recharge estimates to the extent possible. However, the desire to incorporate critical new information, relevant land-cover conditions, or a consistent computation method may require recomputation of existing estimates. Estimates of future groundwater recharge will incorporate published climate projections available at the time this study begins.

This proposed 2.5-year study is estimated to cost $333,000 which will be cost-shared by CWRM ($233,000) and the USGS ($100,000). Results of this study will be documented in a USGS Scientific Investigations Report and associated digital spatial datasets of groundwater recharge that will be made available to the public through the internet. Spatially distributed recharge results will be aggregated by aquifer system and recharge totals by aquifer system will be presented in tabular format in the report.

INTRODUCTION

Reliable estimates of groundwater recharge are critical for evaluating groundwater availability in Hawai‘i. The Hawai‘i Commission on Water Resource Management (CWRM) relies on groundwater-recharge estimates to develop sustainable-yield values for each aquifer system in the State (fig. 1), and these sustainable-yield values are used to evaluate whether rates of groundwater withdrawal are sustainable. Reliable groundwater-recharge estimates also are needed for developing numerical groundwater models that can be used to improve understanding of groundwater availability. With projected increases in demand for groundwater, the need for reliable groundwater-recharge estimates is an important priority for CWRM (State of Hawai‘i, 2018).

Published climate projections for Hawai‘i (Elison Timm and others, 2015; Zhang and others, 2016b) indicate that rainfall is expected to change relative to recent conditions, which has important implications for future groundwater availability. Recognizing that proactive planning is essential for appropriate management of groundwater resources in Hawai‘i, CWRM has identified the need to develop recharge estimates that include best available information on climate-change impacts and to integrate this information into long-range water-resources planning (State of Hawai‘i, 2018).

Published spatial datasets quantifying the recent rainfall (Giambelluca and others, 2013; Frazier and others, 2016) and evapotranspiration (Giambelluca and others, 2014) distributions in Hawai‘i represent the best available information for characterizing recent hydrologic conditions. The U.S. Geological Survey (USGS) incorporated these spatial datasets in water-budget models to estimate spatially distributed groundwater recharge for Kaua‘i, O‘ahu, and Maui for recent conditions (1978–2007 rainfall and 2010 land cover) (Engott and others, 2017; Johnson and others, 2018; Izuka and others, 2018). These water-budget models used a daily computation interval and incorporated the best available information related to evapotranspiration characteristics of native and nonnative forests in Hawai‘i. As part of an ongoing USGS study of the groundwater resources of Moloka‘i, groundwater recharge on Moloka‘i is being estimated using the same rainfall and evapotranspiration datasets (Giambelluca and others, 2013; Frazier and others, 2016; Giambelluca and others, 2014) and water-budget method consistent with the previously published water-budget studies (Engott and others, 2017; Johnson and others, 2018; Izuka and others, 2018). USGS water-budget studies for selected areas in Hawai‘i published prior to 2014 are not consistent with the more recent studies because they did not include a forest-canopy budget, did not differentiate between native and nonnative forest characteristics (with the exception of Engott, 2011), used a different runoff-rainfall model, and used different rainfall and evapotranspiration data with a daily computation interval (Oki, 2002; Izuka and others, 2005; Engott and Vana, 2007; Engott, 2011) or a coarser, monthly computation interval (Shade, 1995a; 1995b; Shade, 1996; Shade and Nichols, 1996; Shade, 1997a; 1997b; Shade, 1999). Thus, the USGS water-budget studies published prior to 2014 will not be considered for this study.

Climate conditions in Hawai'i have changed over the last century with important implications for freshwater availability, agriculture, and ecosystem integrity (Bassiouni and Oki, 2013; Chu and Chen, 2005; Giambelluca and others, 2008; Oki, 2004). The interaction of prevailing northeast trade winds with island topography creates steep rainfall gradients on each island, with mean annual rainfall varying by more than a factor of 15 over 6 miles or less in places (Schroeder, 1993; Giambelluca and others, 2013). High-resolution climate information is needed to understand how groundwater recharge varies spatially. Recent downscaling of phases 3 and 5 of the Coupled Model Intercomparison Project (CMIP3 and CMIP5) model experiments using dynamical- and statistical-downscaling methods have produced high-resolution projected climate information for the Hawaiian Islands (Timm and Diaz, 2009; Elison Timm and others, 2015; Wang and others, 2016; Zhang and others, 2016b; Elison Timm, 2017). Collectively, these climate projections show high spatial variability and a range of projected rainfall changes. Future rainfall projections have been developed for the Hawaiian Islands, using different downscaling approaches, spatial resolutions, time frames, and emission scenarios (Elison Timm and others, 2015; Zhang and others, 2016b), and these published climate projections will lead to different future recharge estimates.

Elison Timm and others (2015) used a statistical-downscaling approach and a 250-meter grid spacing to produce wet (November–April) and dry (May–October) season rainfall anomalies for two time periods (2041–71 and 2071–99) for two CMIP5 Representative Concentration Pathways (RCP) scenarios with total radiative forcing of 4.5 and 8.5 watts per square meter by the year 2100 (Intergovernmental Panel on Climate Change, 2013). The seasonal rainfall anomalies computed by Elison Timm and others (2015) for the RCP4.5 and RCP8.5 scenarios represent departures from seasonal rainfall during 1978–2007 that were estimated by Giambelluca and others (2013). Elison Timm (2017) used a statistical-downscaling approach and a 250-meter grid spacing to develop projections of surface air temperature anomalies for two time periods (2040–69 and 2070–99) for RCP4.5 and RCP8.5 scenarios. The ambient surface temperature anomalies for the RCP scenarios were computed relative to a 1976–2005 reference period.

Zhang and others (2012) used a dynamical-downscaling approach and a 3-km grid spacing to develop a one-year retrospective simulation (November 2005 to October 2006) by configuring a Hawai‘i regional climate model for the main Hawaiian Islands and surrounding ocean region. Zhang and others (2012) simulated the interaction of sea-surface temperature, cloud-base height, trade-wind strength and direction, and trade-wind inversion height and frequency with topography. They produced simulated output of meteorological parameters including rainfall, surface temperature, relative humidity, and wind speed and direction. Lauer and others (2013) noted limitations in the simulated rainfall over areas with steep topography, particularly on the islands of Maui and O‘ahu. Zhang and others (2016a) used a dynamical-downscaling approach and a 3-km grid spacing to simulate climate for the main Hawaiian Islands during 1990–2009, and also simulated climate for Maui using a 1-km resolution to address the limitations noted by Lauer and others (2013).

Zhang and others (2016b) used the dynamical-downscaling approach and a 3-km grid spacing to project climate for the main Hawaiian Islands for end-of-century conditions (2080–99) considering the "CMIP3 Special Report on Emissions Scenarios" A1B emission scenario (Intergovernmental Panel on Climate Change, 2000). Zhang and others (2016b) also projected climate for Maui for the same conditions, with the exception of a 1-km grid spacing, to evaluate the importance of spatial resolution on results. Projections for Maui using the refined, 1-km grid spacing indicate greater projected rainfall in wet areas relative to projections using the 3-km grid spacing. Recently, researchers at the University of Hawai‘i used dynamical downscaling and an 800-m grid spacing to project climate for the main Hawaiian Islands during 2080–99 for the RCP4.5 and RCP8.5 scenarios, although these projections have not been published as of February 2019.

Generally, statistical downscaling from global models projects overall drier conditions and dynamical downscaling projects overall wetter conditions, although the projections indicate some degree of agreement with certain wet windward areas projected to become wetter and certain leeward dry areas projected to become drier. The climate changes are projected to become more pronounced with more aggressive drivers (RCP8.5, A1B) and longer timeframes (end-of-century scenarios).

As part of published and ongoing studies, USGS has estimated, or is in the process of estimating, groundwater recharge for Kaua'i, O'ahu, Moloka'i, Maui, and Hawai'i for recent climate conditions (1978–2007) and a range of end-of-century (2080–99) projected climate conditions. (Groundwater-recharge estimates currently do not exist for Lāna'i using datasets and methods consistent with estimates from the other islands and therefore Lāna'i is not included in this study, although Lāna'i could be considered in future efforts.) In some cases, published groundwater recharge estimates may reflect land-cover conditions that may no longer be relevant for planning purposes. For example, published recharge estimates for Maui (Johnson and others, 2018; Izuka and others, 2018) include large areas of sugarcane, which has not been cultivated since the end of 2016. Furthermore, estimates of groundwater recharge for projected mid-century conditions currently do not exist. Given the recent availability of future climate projections, CWRM is interested in understanding possible impacts on groundwater recharge for a 20- to 30-year planning horizon typically used by water utilities and resource managers. This proposed study will address CWRM needs for groundwater-recharge estimates needed for proactive planning and water management in the State.

PROBLEM

Projected water demand in Hawai'i is expected to increase from 239 to 269 million gallons per day (Mgal/d) from 2020 to 2035 (State of Hawai'i, 2018). Depending on location, some of this increase in demand will be met by groundwater sources. Available climate projections for mid-century (2041–71) conditions indicate that rainfall may decrease in many areas of the state, including areas where groundwater is heavily developed (Elison Timm and others, 2015). Projected increases in water demand coupled with projected decreases in rainfall suggest a need for proactive planning and water management. As part of its priorities and action plan (State of Hawai'i, 2018), CWRM recognizes the need to improve recharge estimates to include the best available information on climate-change impacts and to integrate the best available information on the impacts of climate change on long-range water resources planning. Estimates of future groundwater recharge based on published climate projections for a mid-century time frame will enable CWRM to evaluate how groundwater availability may be affected by climate change over a water-resources planning horizon (20 to 30 years) and potentially adjust sustainable-yield values.

OBJECTIVES AND SCOPE

The overall objective of this study is to quantify potential changes in groundwater recharge, relative to recent conditions, for the main Hawaiian Islands of Kaua'i, O'ahu, Moloka'i, Maui, and Hawai'i. To quantify these changes, existing groundwater-recharge estimates will be used, or updated estimates will be developed, for recent conditions (1978–2007), mid-century projected climate conditions, and end-of-century projected climate conditions. Consistent climate datasets and methods will be used to enable meaningful comparisons among time periods and islands to be made. These groundwater-recharge estimates are needed to evaluate the potential effects of climate change on water availability and groundwater-dependent ecosystems. To control costs, this study will use existing USGS recharge estimates to the extent possible. However, changes in land-cover conditions or newly available information on water-budget components (published after the existing USGS recharge estimates were developed) may need to be considered, which could necessitate recomputation of recharge for some islands and periods. Estimates of future groundwater recharge will incorporate published climate projections available at the time this study begins.

RELEVANCE AND BENEFITS

Groundwater recharge estimates that will result from this study are needed for the management of limited water resources in the State of Hawai'i. CWRM requires estimates of future groundwater recharge to evaluate how sustainable-yield values may change throughout the State and potentially affect water management. In addition, estimates of future groundwater recharge will (1) enhance understanding of where to prioritize watershed-management efforts and ecohydrology studies, (2) provide information needed to develop numerical groundwater models that will be useful for evaluating potential changes to groundwater systems and natural discharges, and (3) enable characterization of the relative impacts of climate change and land-use change on groundwater recharge. This study will provide the latest information needed for planning and management of groundwater resources and will enhance knowledge of the effects of climate change on groundwater availability and groundwater-dependent ecosystems in the State.

APPROACH

A water-budget model of the plant root zone will be used to compute the spatial distribution of groundwater recharge for the islands of Kaua'i, O'ahu, Moloka'i, Maui, and Hawai'i for recent (1978–2007) conditions (as needed) and mid-century (2041–71) projected climate conditions using consistent climate datasets and computation methods. To the extent possible, published recharge estimates for recent (1978–2007) conditions will be incorporated in this study, although incorporation of critical new research, relevant land-cover conditions, or a consistent computation method may require updates to published estimates. For this study, a daily computation interval will be used in the water budget to avoid potential biases associated with coarser (monthly or annual) computation intervals. The water-budget model accounts for daily changes in soil moisture in the plant root-zone system related to water inputs (rainfall, fog interception, and irrigation) and outputs (runoff and evapotranspiration). The computation methods have been previously documented (Engott and others, 2017; Johnson and others, 2018; Izuka and others, 2018). The reader is referred to the cited references for details related to the water-budget computation approach that will be used in this proposed study.

Water-Budget Code

Previously published USGS water budgets for Hawai'i have used a geographic-information system (GIS) approach that discretizes the island using irregularly shaped subareas, each with uniform hydrologic properties (see, for example, Engott and others, 2017; Johnson and others, 2018; Izuka and others, 2018). For this study, consideration will be given to developing spatial recharge estimates using a grid-based approach (Westenbroek and others, 2018), in which the island is discretized using a regular grid. Use of the grid-based approach will enable incorporation of results in a web-based interface tool, which is being developed by the USGS in cooperation with the University of Hawai'i, for evaluating how groundwater recharge changes in response to land-cover and climate changes.

Land-Cover Conditions

To isolate the effects of climate change on groundwater recharge, the same land-cover conditions will be used to estimate groundwater recharge for recent (1978–2007) and future climate conditions for each island. Published groundwater-recharge estimates for recent conditions on Maui (Johnson and others, 2018) do not reflect the cessation of sugarcane cultivation on Maui in 2016. For this study, updated recharge estimates reflecting relevant recent land-cover conditions will be developed as needed. The best available land-cover maps will be used and modified as appropriate to reflect recent conditions.

Soil and Vegetation Properties

Soil properties needed in the water-budget model will be based on published soil survey geographic (SSURGO) datasets from the Natural Resources Conservation Service (https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/). Vegetation properties, including root depth, canopy capacity, trunk-storage capacity, and evapotranspiration crop coefficient, will be based on published estimates (Engott and others, 2017; Johnson and others, 2018; Izuka and others, 2018) or critical new information that becomes available prior to the start of this study.

Irrigation

Irrigation rates will be determined using supply-based estimates where data permit and demand-based estimates elsewhere. Methods used to estimate irrigation rates will be consistent with previously published methods (Engott and others, 2017; Johnson and others, 2018).

Runoff

Where streamflow-gaging stations were operated during the period 1978–2007, runoff can be estimated from the streamflow data using base-flow separation methods (see for example, Wahl and Wahl, 1995). In ungaged areas, published regression equations (Engott and others, 2017; Johnson and others, 2018; Izuka and others, 2018) will be used where appropriate. In some areas on the island of Hawai‘i, permeable soils and rocks at the land surface may preclude large amounts of runoff and these areas may be considered separately (Engott, 2011).

Recent Climate Conditions

Estimates of groundwater recharge for recent climate conditions will incorporate published rainfall for the period 1978–2007 (Giambelluca and others, 2013; Frazier and others, 2016) and best available reference evapotranspiration data for the State (Giambelluca and others, 2014). Fog interception may be present above an altitude of about 2,000 ft, within the cloud-forming zone on mountain slopes. Estimates of the rates and distributions of fog interception will be based on published methods (Engott and others, 2017; Johnson and others, 2018). Groundwater recharge estimated using the selected recent climate conditions will be used to provide a consistent baseline for comparison with recharge for projected future conditions to evaluate recharge changes related to climate.

Projected Climate Conditions

As part of an ongoing USGS study, groundwater recharge for end-of-century conditions is being estimated for Kaua'i, O'ahu, Moloka'i, Maui, and Hawai'i for a range of projected climate conditions (wetter and drier) (Zhang and others, 2016b; Elison Timm and others, 2015). These estimates will be incorporated in this study unless updates to the estimates are needed to address consistency criteria. As part of this study, groundwater recharge for mid-century conditions will be estimated for Kaua'i, O'ahu, Moloka'i, Maui, and Hawai'i. Currently, projected rainfall for mid-century conditions is available for RCP4.5 and RCP8.5 scenarios using statistical-downscaling methods (Elison Timm and others, 2015). If no other statewide projections for mid-century conditions are available at the time this study begins, the existing projected mid-century (2041–71) rainfall for the RCP8.5 scenario (Elison Timm and others, 2015) will be incorporated in this study. Projected rainfall for the RCP8.5 scenario would be selected over the RCP4.5 scenario to provide greater contrast (drier conditions) relative to recent conditions, which is consistent with "a precautionary and adaptive approach to water management to ensure the long-term protection of our water resources…" (State of Hawaii, chapter 1, p. 10).

Methods used to incorporate projected climate information into the water-budget model have been developed for Maui as part of a separate USGS study (Alan Mair, U.S. Geological Survey, written commun., 2019). These methods are expected to be used for this proposed study as well.

PRODUCTS

Results of this study will be documented in a USGS Scientific Investigations Report that will be made available to the public through the internet. In addition, digital spatial datasets of groundwater recharge for recent (1978–2007) and projected future conditions will be published and made available to the public through the internet. Spatially distributed recharge results will be aggregated by aquifer system and recharge totals by aquifer system will be presented in tabular format in the report. This study will take 2.5 years to complete once initiated. CWRM staff will be kept informed of progress and findings through scheduled meetings and quarterly progress updates.

Table 1. Milestone dates for planned products.

Probable title	Product outlet	First draft	Review	Approval	Publication
Assessment of groundwater recharge for recent, mid-century, and end-of-century climate conditions, Hawai'i	USGS SIR	2/2021	05/2021	08/2021	11/2021
Recharge datasets for Kaua'i, O'ahu, Maui, Moloka'i, and Hawai'i for mid-century projected climate conditions (statistical downscaling-method, RCP8.5)	ScienceBase	2/2021	05/2021	08/2021	11/2021
Additional recharge datasets that may be required to produce consistent recharge estimates for the State	ScienceBase	2/2021	05/2021	08/2021	11/2021

TIMELINE

The major tasks and associated timelines for this study are summarized in Table 2.

Table 2. Major study tasks and timelines.

	2019				2020				2021			
Task	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
Obtain and process datasets		X	X	X								
Prepare input files			X	X	X	X	X	X				
Compute and analyze water budget			X	X	X	X	X	X				
Publication (datasets and report)												
Prepare draft							X	X	X			
Review										X		
Approval											X	
Publish on internet												X

BUDGET

This proposed 2.5-year study is estimated to cost $333,000 which will be cost-shared by CWRM ($233,000) and the USGS ($100,000). A cost breakdown is provided in Table 3. Labor includes salary and indirect costs for leave, facilities, and overhead assessments. Science support includes indirect costs for project management, technical services, and report processing fees. Progress letters summarizing status of the study will be provided on a quarterly basis.

Table 3. Project budget by federal fiscal year.

Category	Total
Labor	$ 298,300
Science support	$ 34,700
Total	**$ 333,000**
CWRM	$ 233,000
USGS	$ 100,000

REFERENCES

Bassiouni, M., and Oki, D.S., 2013, Trends and shifts in streamflow in Hawai'i, 1913–2008: Hydrological Processes, v. 27, no. 10, p. 1484–1500.

Chu, P.-S., and Chen, H., 2005, Interannual and interdecadal rainfall variations in the Hawaiian Islands: Journal of Climate, v. 18, p. 4796–4813.

Elison Timm, O., 2017, Future warming rates over the Hawaiian Islands based on elevation-dependent-scaling factors: International Journal of Climatology, v. 37, p. 1093–1104, doi: 10.1002/joc.5065.

Elison Timm, O., Giambelluca, T.W., and Diaz, H.F., 2015, Statistical downscaling of rainfall changes in Hawai'i based on the CMIP5 global model projections: Journal of Geophysical Research: Atmospheres, v. 120, no. 1, p. 92–112, doi: 10.1002/2014JD022059.

Engott, J.A., 2011, A water-budget model and assessment of groundwater recharge for the Island of Hawai'i: U.S. Geological Survey Scientific Investigations Report 2011–5078, 53 p.

Engott, J.A., Johnson, A.G., Bassiouni, M., Izuka, S.K., and Rotzoll, K., 2017, Spatially distributed groundwater recharge for 2010 land cover estimated using a water-budget model for the Island of O'ahu, Hawai'i (ver. 2.0, December 2017): U.S. Geological Survey Scientific Investigations Report 2015–5010, 49 p., https://doi.org/10.3133/sir20155010.

Engott, J.A., and Vana, T.T., 2007, Effects of agricultural land-use changes and rainfall on ground-water recharge in central and west Maui, Hawai'i, 1926–2004: U.S. Geological Survey Scientific Investigations Report 2007–5103, 56 p.

Evenson, E.J., Orndorff, R.C., Blome, C.D., Bohlke, J.K., Herschberger, P.K., Langenheim, V.E., McCabe, G.J., Morlock, S.E., Reeves, H.W., Verdin, J.P., Weyers, H.S., and Wood, T.M., 2012, Strategic directions for U.S. Geological Survey water science, 2012–2022—Observing, understanding, predicting, and delivering water science to the Nation: U.S. Geological Survey Open-File Report 2012–1066, 42 p., https://pubs.usgs.gov/of/2012/1066/.

Frazier, A.G., Giambelluca, T.W., Diaz, H.F., and Needham, H.L., 2016, Comparison of geostatistical approaches to spatially interpolate month-year rainfall for the Hawaiian Islands: International Journal of Climatology, v. 36, no. 3, p. 1459–1470, at http://dx.doi.org/10.1002/joc.4437.

Giambelluca, T.W., Chen, Q., Frazier, A.G., Price, J.P., Chen, Y.-L., Chu, P.-S., Eischeid, J.K., and Delparte, D.M., 2013, Online Rainfall Atlas of Hawai'i: Bulletin of the American Meteorological Society, v. 94, p. 313–316, doi: 10.1175/BAMS-D-11-00228.1, at http://rainfall.geography.hawaii.edu/.

Giambelluca, T.W., Diaz, H.F., and Luke, M.S.A., 2008, Secular temperature changes in Hawaii: Geophysical Research Letters, v. 35, p. L12702.

Giambelluca, T.W., Shuai, Xiufu, Barnes, M.L., Alliss, R.J., Longman, R.J., Miura, Tomoaki, Chen, Qi, Frazier, A.G., Mudd, R.G., Cuo, Lan, and Businger, A.D., 2014, Evapotranspiration of Hawai'i: Final report, submitted to U.S. Army Corps of Engineers–Honolulu District and Commission on Water Resource Management, State of Hawai'i, 178 p.

Intergovernmental Panel on Climate Change, 2000, Special Report on Emissions Scenarios (SRES) (Nakicenovic, Nebojsa & Swart, Rob, Eds.): Cambridge University Press, Cambridge, United Kingdom, 570 p.

Intergovernmental Panel on Climate Change, 2013, Climate change 2013, the physical science basis, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P. M. Midgley, Eds.): Cambridge University Press, Cambridge, UK and New York, USA.

Izuka, S.K., Engott, J.A., Rotzoll, K., Bassiouni, M., Johnson, A.G., Miller, L.D., and Mair, A., 2018, Volcanic aquifers of Hawai'i—Hydrogeology, water budgets, and conceptual models (ver. 2.0, March 2018): U.S. Geological Survey Scientific Investigations Report 2015-5164, 158 p., https://doi.org/10.3133/sir20155164.

Izuka, S.K., Oki, D.S., and Chen, C.H., 2005, Effects of irrigation and rainfall reduction on ground-water recharge in the Lihue Basin, Kauai, Hawaii: U.S. Geological Survey Scientific Investigations Report 2005–5146, 48 p.

Johnson, A.G., Engott, J.A., Bassiouni, M., and Rotzoll, K., 2018, Spatially distributed groundwater recharge estimated using a water-budget model for the Island of Maui, Hawai`i, 1978–2007 (ver. 2.0, February 2018): U.S. Geological Survey Scientific Investigations Report 2014–5168, 53 p., https://doi.org/10.3133/sir20145168.

Oki, D.S., 2002, Reassessment of ground-water recharge and simulated ground-water availability for the Hawi area of north Kohala, Hawaii: U.S. Geological Survey Water-Resources Investigations Report 02–4006, 62 p.

Oki, D.S., 2004, Trends in streamflow characteristics at long-term gaging stations, Hawai'i: U.S. Geological Survey Scientific Investigations Report 2004–5080, 116 p.

Schroeder, T.A., 1993, Climate controls, chap. 2 *of* Sanderson, M. ed., Prevailing trade winds, weather and climate in Hawai'i: Honolulu, University of Hawai'i Press, p. 12–36.

Shade, P.J., 1995, Water budget for the island of Kauai, Hawaii. U.S. Geological Survey Water-Resources Investigations Report, 95–4128, 25 p.

Shade, P.J., 1995, Water budget for the Kohala area, island of Hawaii. U.S. Geological Survey Water-Resources Investigations Report, 95–4114, 19 p.

Shade, P.J., 1996, Water budget for the Lahaina District, island of Maui, Hawaii: U.S. Geological Survey Water-Resources Investigations Report 96–4238, 27 p.

Shade, P.J., 1997, Water budget for the Iao area, island of Maui, Hawaii: U.S. Geological Survey Water-Resources Investigations Report 97-4244, 25 p.

Shade, P.J., 1997, Water budget for the island of Molokai, Hawaii: U.S. Geological Survey Water-Resources Investigations Report 97–4155, 20 p.

Shade, P.J., 1999, Water budget of East Maui, Hawaii: U.S. Geological Survey Water-Resources Investigations Report 98–4159, 36 p.

Shade, P.J., and Nichols, W.D., 1996, Water budget and the effects of land-use changes on ground-water recharge, Oahu, Hawaii: U.S. Geological Survey Professional Paper 1412–C, 38 p.

State of Hawaiʻi, 2018, Water resource protection plan, 2019 update: State of Hawaiʻi, Commission on Water Resource Management, variously paged, accessed January 29, 2019, at https://dlnr.hawaii.gov/cwrm/planning/hiwaterplan/wrpp/.

Timm, O., and Diaz, H.F., 2009, Synoptic-statistical approach to regional downscaling of IPCC twenty-first-century climate projections: seasonal rainfall over the Hawaiian Islands: Journal of Climate, v. 22, p. 4261–4280, doi: 10.1175/2009JCLI2833.1.

U.S. Geological Survey, 2007, Facing tomorrow's challenges—U.S. Geological Survey science in the decade 2007–2017: U.S. Geological Survey Circular 1309, x + 70 p., https://pubs.usgs.gov/circ/2007/1309/.

Wahl, K.L., and Wahl, T.L., 1995, Determining the flow of Comal Springs at New Braunfels, Texas: Proceedings of Texas Water '95, a component conference of the American Society of Civil Engineers International Conference on Water Resources Engineering, 1st, San Antonio, Texas, 1995, p. 77–86.

Wang, Y., Chunxi, Z., Axel, L., and Kevin, H., 2016, Hawaii regional climate model simulations (HRCM): Asia-Pacific Data-Research Center, International Pacific Research Center, accessed August 3, 2016, at http://apdrc.soest.hawaii.edu/projects/HRCM/.

Westenbroek, S.M., Engott, J.A., Kelson, V.A., and Hunt, R.J., 2018, SWB Version 2.0—A Soil-Water-Balance code for estimating net infiltration and other water-budget components: U.S. Geological Survey Techniques and Methods, book 6, chap. A59, 118 p., https://doi.org/10.3133/tm6A59.

Zhang, C., Wang, Y., Hamilton, K., and Lauer, A., 2016a, Dynamical downscaling of the climate for the Hawaiian Islands, part I, present day: Journal of Climate, v. 29, no. 8, p. 3027–3048, doi:10.1175/JCLI-D-15-0432.1.

Zhang, C., Wang, Y., Hamilton, K., and Lauer, A., 2016b, Dynamical downscaling of the climate for the Hawaiian Islands, part II, projection for the late twenty-first century: Journal of Climate, v. 29, no. 23, p. 8333–8354, doi: 10.1175/JCLI-D-16-0038.1.

Zhang, C., Wang, Y., Lauer, A., and Hamilton, K., 2012, Configuration and evaluation of the WRF model for the study of Hawaiian regional climate: Monthly Weather Review, v. 140, no. 10, p. 3259–3277, doi: 10.1175/MWR-D-11-00260.1.

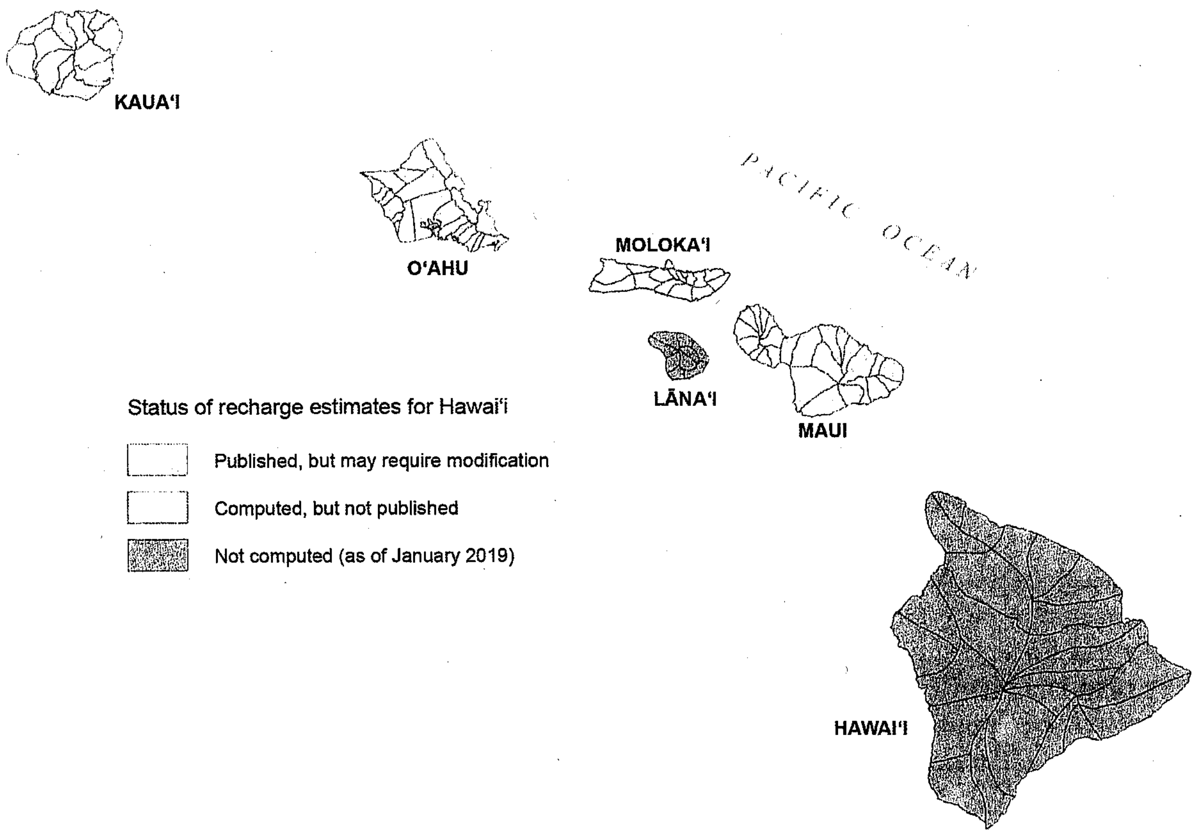

Figure 1. Aquifer systems (State of Hawaiʻi, 2018), and status (as of February 2019) of USGS groundwater recharge estimates computed using recent evapotranspiration and rainfall datasets for the 1978–2007 period, Hawaiʻi.

Groundwater Recharge for Recent and Future Climate Conditions, Lāna‘i, Hawai‘i

U.S. Geological Survey
Pacific Islands Water Science Center
Proposal, February 2019

SUMMARY

Projected increases in water demand coupled with projected decreases in rainfall suggest a need for proactive planning and water management on Lāna‘i. The Hawai‘i Commission on Water Resource Management (CWRM) recognizes the need to improve groundwater recharge estimates to include the best available information on climate-change impacts and to integrate the best available information on the impacts of climate change on long-range water resources planning. Estimates of future groundwater recharge based on published climate projections will enable CWRM to evaluate how groundwater availability may be affected by climate change over a 20- to 50-year water-resources planning horizon and potentially adjust sustainable-yield values.

The overall objective of this study is to quantify (1) the distribution of groundwater recharge on Lāna‘i for recent climate conditions (1978–2007), (2) the distribution of groundwater recharge for drought conditions (determined from the five consecutive years during 1978–2007 with the lowest island-wide rainfall), and (3) potential future changes in groundwater recharge associated with selected climate projections relative to recent conditions. A water-budget model will be used to estimate groundwater recharge for recent conditions (1978–2007), recent drought conditions, mid-century projected climate conditions (2041–71), and a range of end-of-century projected climate conditions. These groundwater-recharge estimates are needed to evaluate the potential effects of climate change on water availability and groundwater-dependent ecosystems. Estimates of future groundwater recharge will incorporate published climate projections for Lāna‘i available at the time this study begins. Climate datasets and computation methods consistent with those used for the other main Hawaiian islands will be used in this study to enable comparisons among time periods and islands to be made.

This proposed 2.5-year study is estimated to cost $320,000 which will be cost-shared by CWRM ($224,000) and the USGS ($96,000). Results of this study will be documented in a USGS Scientific Investigations Report and associated digital spatial datasets of groundwater recharge that will be made available to the public through the internet. Spatially distributed recharge results will be aggregated by aquifer system and recharge totals by aquifer system will be presented in tabular format in the report.

INTRODUCTION

Reliable estimates of groundwater recharge are critical for evaluating groundwater availability in Hawaiʻi. The Hawaiʻi Commission on Water Resource Management (CWRM) relies on groundwater-recharge estimates to develop sustainable-yield values for each aquifer system in the State, and these sustainable-yield values are used to evaluate whether rates of groundwater withdrawal are sustainable. Reliable groundwater-recharge estimates also are needed for developing numerical groundwater models that can be used to improve understanding of groundwater availability. With projected increases in demand for groundwater, the need for reliable groundwater-recharge estimates is an important priority for CWRM (State of Hawaiʻi, 2018b). To date, CWRM does not have groundwater-recharge estimates for the island of Lānaʻi that incorporate the best available rainfall and evapotranspiration datasets (Giambelluca and others, 2013; Frazier and others, 2016; Giambelluca and others, 2014) and water-budget method consistent with previously published U.S. Geological Survey (USGS) water-budget studies (Engott and others, 2017; Johnson and others, 2018; Izuka and others, 2018).

Published spatial datasets quantifying the recent rainfall (Giambelluca and others, 2013; Frazier and others, 2016) and evapotranspiration (Giambelluca and others, 2014) distributions in Hawaiʻi represent the best available information for characterizing recent hydrologic conditions. The USGS incorporated these spatial datasets in water-budget models to estimate spatially distributed groundwater recharge for Kauaʻi, Oʻahu, and Maui for recent conditions (1978–2007 rainfall and 2010 land cover) (Engott and others, 2017; Johnson and others, 2018; Izuka and others, 2018). These water-budget models used a daily computation interval and incorporated the best available information related to evapotranspiration characteristics of native and nonnative forests in Hawaiʻi. As part of an ongoing USGS study of the groundwater resources of Molokaʻi, groundwater recharge on Molokaʻi is being estimated using the same rainfall and evapotranspiration datasets (Giambelluca and others, 2013; Frazier and others, 2016; Giambelluca and others, 2014) and water-budget method consistent with the previously published water-budget studies (Engott and others, 2017; Johnson and others, 2018; Izuka and others, 2018). Comparable groundwater-recharge estimates for Lānaʻi currently are not available.

Climate conditions in Hawaiʻi have changed over the last century with important implications for freshwater availability, agriculture, and ecosystem integrity (Bassiouni and Oki, 2013; Chu and Chen, 2005; Giambelluca and others, 2008; Oki, 2004). The interaction of prevailing northeast trade winds with island topography creates steep rainfall gradients on each island, with mean annual rainfall varying by more than a factor of 15 over 6 miles or less in places (Schroeder, 1993; Giambelluca and others, 2013). High-resolution climate information is needed to understand how groundwater recharge varies spatially. Recent downscaling of phases 3 and 5 of the Coupled Model Intercomparison Project (CMIP3 and CMIP5) model experiments using dynamical- and statistical-downscaling methods have produced high-resolution projected climate information for the Hawaiian Islands, including Lāna'i (Timm and Diaz, 2009; Elison Timm and others, 2015; Wang and others, 2016; Zhang and others, 2016; Elison Timm, 2017). Future rainfall projections have been developed for Lāna'i, using different downscaling approaches, spatial resolutions, time frames, and emission scenarios (Elison Timm and others, 2015; Zhang and others, 2016), and these published climate projections will lead to different future recharge estimates. Future changes in groundwater recharge have important implications for future groundwater availability. Recognizing that proactive planning is essential for appropriate management of groundwater resources in Hawai'i, CWRM has identified the need to develop recharge estimates that include best available information on climate-change impacts and to integrate this information into long-range water-resources planning (State of Hawai'i, 2018b).

Elison Timm and others (2015) used a statistical-downscaling approach and a 250-meter grid spacing to produce wet (November–April) and dry (May–October) season rainfall anomalies for two time periods (2041–71 and 2071–99) for two CMIP5 Representative Concentration Pathways (RCP) scenarios with total radiative forcing of 4.5 and 8.5 watts per square meter by the year 2100 (Intergovernmental Panel on Climate Change, 2013). The seasonal rainfall anomalies computed by Elison Timm and others (2015) for the RCP4.5 and RCP8.5 scenarios represent departures from seasonal rainfall during 1978–2007 that were estimated by Giambelluca and others (2013).

Zhang and others (2016) used the dynamical-downscaling approach and a 3-km grid spacing to project climate for the main Hawaiian Islands for end-of-century conditions (2080–99) considering the "CMIP3 Special Report on Emissions Scenarios" A1B emission scenario (Intergovernmental Panel on Climate Change, 2000). Zhang and others (2016) also projected climate for Maui for the same conditions, with the exception of a 1-km grid spacing, to evaluate the importance of spatial resolution on results. Projections for Maui using the refined, 1-km grid spacing indicate greater projected rainfall in wet areas relative to projections using the 3-km grid spacing. Recently, researchers at the University of Hawai'i used dynamical downscaling and an

800-m grid spacing to project climate for the main Hawaiian Islands during 2080–99 for the RCP4.5 and RCP8.5 scenarios, although these projections have not been published as of February 2019.

Generally, both statistical and dynamical downscaling from global models project overall drier conditions for Lāna‘i, although the projections indicate some differences in the magnitude and distribution of drying. The climate changes are projected to become more pronounced with more aggressive drivers (RCP8.5, A1B) and longer timeframes (end-of-century scenarios).

As part of published, ongoing, and proposed studies, USGS has estimated, is in the process of estimating, or is planning to estimate groundwater recharge for the islands of Kaua‘i, O‘ahu, Moloka‘i, Maui, and Hawai‘i for recent climate conditions (1978–2007), mid-century (2041–71) projected climate conditions, and a range of end-of-century (2080–99) projected climate conditions. This proposed study will address CWRM needs for comparable groundwater-recharge estimates for Lāna‘i for recent climate conditions (1978–2007), historical drought conditions during 1978–2007, mid-century (2041–71) projected climate conditions, and a range of end-of-century (2080–99) projected climate conditions. Groundwater-recharge estimates for Lāna‘i are needed for proactive planning and water management on the island.

DESCRIPTION OF STUDY AREA

The study area is the island of Lāna‘i (fig. 1), the sixth largest of the eight main Hawaiian islands. Lāna‘i was formed by a single shield volcano and has an area of about 141 square miles (Juvik and Juvik, 1998). The resident population of Lāna‘i was 3,155 in 2010, and averaged 3,455 during 2012–16 (State of Hawai‘i, 2018a). About 98 percent of the island currently is privately owned by Larry Ellison (Gomes, 2017).

During the period from about 1899–1901, sugarcane was cultivated on two plantations on Lāna‘i, one near the northeast coast of the island (Maunalei Sugar Company) and the other in the central part of the island (Palawai Development Company) (Dorrance and Morgan, 2000). These sugarcane plantations were short-lived, which was attributed to a lack of water (Dorrance and Morgan, 2000). Because pineapple plants require much less water than sugarcane, large-scale pineapple-plantation agriculture was successful during much of the 20th century on Lāna‘i. In 1922, James D. Dole purchased nearly the entire island of Lāna‘i to cultivate pineapple in the central part of the island near Lāna‘i City as part of the Hawaiian Pineapple Co. (Hawkins, 2007), which later was renamed after Dole (The Pineapple Growers Association of Hawaii, 1973). Plantation-scale pineapple cultivation on Lāna'i ceased in the early 1990s, and the economy is now driven mainly by tourism with plans for developing a sustainable community through large-scale hydroponic farming methods (Gomes, 2017).

Physical Setting.— The island of Lāna'i was formed by eruptions from Lāna'i Volcano, a shield volcano with three main rift zones that trend northwest, southwest, and southeast from a central caldera area. Exposed rocks on Lāna'i are shield-stage lavas consisting mainly of tholeiitic basalt, olivine tholeiitic basalt, and picritic tholeiitic basalt (Langenheim and Clague, 1987). The summit area of the shield volcano collapsed, forming a caldera that was later partly filled by lava flows.

Except where modified by erosion or faulting, the land surface of Lāna'i is generally gently sloped, rising from sea level at the coast to a peak altitude of 3,366 ft near the central part of the island. About 46 percent of the land surface of Lāna'i is below an altitude of 1,000 ft and about 94 percent is below an altitude of 2,000 ft. Less than 0.5 percent of the land surface is above an altitude of 3,000 ft. Along the southwest shoreline, marine erosion, perhaps partly related to a large-scale debris avalanche on the unbuttressed side of the volcano (Moore and others, 1989), has created steep sea cliffs, rising nearly a thousand feet above the ocean in places. Stream erosion has carved deep valleys on the northeast slopes of the island. Stearns (1940) indicated that the only perennial stream on Lāna'i was Maunalei Gulch, although long-term streamflow data are not available to determine whether the stream flowed continuously to the coast. Streams on Lāna'i are short, with steep gradients and small drainage basins. Thus, streamflow is likely flashy as it is in other Hawaiian streams (Oki, 2003). Because of a lack of reliable surface-water resources, groundwater is the main source of water for Lāna'i.

Vegetation on Lāna'i has been modified by human activities and perhaps by goats, cattle, sheep, deer, and other animals. Stearns (1940) indicated that wild goats were largely responsible for the destruction of vegetation on Lāna'i and the spread of nonnative grasses to the areas that were denuded. Vegetation today consists mainly of shrubland and grassland below an altitude of 1,000 ft; a mixture of shrubland, grassland, introduced forest species, and developed and barren areas between altitudes of 1,000 and 2,000 ft; and forest land above an altitude of 2,000 ft.

Climate.—The climate of Lāna'i is subtropical and is characterized by mild temperatures, moderate to high humidity, prevailing northeasterly trade winds, and relatively low rainfall. Average annual rainfall on Lāna'i ranges from less than 20 in. near the coast to more than 35 in. inland (Giambelluca and others, 2013) and is largely controlled by the interaction of topography with the trade winds. Because Lānaʻi lies in the rain shadow of Maui and Molokaʻi, and because the island does not rise extensively into the cloud-forming zone, rainfall is less than it is on most of the other Hawaiian islands. Rainfall generally is highest during the months of November to February, and lowest during the months of June to September.

Cloud water intercepted by vegetation and that subsequently drips to the ground (fog drip) may contribute substantially to the water budget of the island (Ekern, 1964; Juvik and others, 2011). In a seminal study of cloud-water interception in Hawaiʻi, Ekern (1964) indicated that cloud-water interception by a Norfolk Island pine tree (*Araucaria heterophylla*) growing near the summit of Lānaʻi contributed about 30 in. annually, or about 60 percent of average annual rainfall (50 in.) during the 3-year measurement period. Juvik and others (2011) resurveyed cloud-water interception on the exposed mountain ridge on Lānaʻi during 2006–08 and measured substantially higher rates of cloud-water interception (181 to 462 percent of measured rainfall), which was attributed to (1) more robust estimates of non-vertical rainfall, (2) taller trees with greater fog-capturing capacity, and (3) greater cloud-water occurrence at higher altitudes.

Groundwater Occurrence.—Groundwater occurs in two main forms on the island of Lānaʻi: (1) as a freshwater-lens system in dike-free volcanic rocks, and (2) as dike-confined groundwater in the interior part of the island. Because of low rates of rainfall and groundwater recharge on Lānaʻi, combined with mixing of saltwater derived from the ocean with fresher water in the permeable dike-free volcanic rocks, the freshwater-lens system contains limited fresh groundwater. Drilled wells and shallow dug wells near the coast generally produce water from the freshwater-lens system that is too brackish for human consumption (Stearns, 1940). The water table of the freshwater-lens system generally is less than a few feet above sea level.

Dike-confined groundwater occurs mainly in the central part of the island. Groundwater in dike compartments also may exist near the coast where dikes are aligned roughly perpendicular to the coast, which allows saltwater derived from the ocean to mix with fresher groundwater. The main body of dike-confined groundwater is in the interior part of the island where groundwater levels are hundreds to more than a thousand feet above sea level. The dike-confined groundwater is the main source of drinking water on Lānaʻi. This study will provide estimates of recent and future groundwater recharge over Lānaʻi, including the main area of groundwater development in the central part of the island.

PROBLEM

Projected groundwater demand on Lāna'i is expected to increase from an existing (2016) demand of about 1.8 million gallons per day (Mgal/d) to 3.7 Mgal/d by 2030 (State of Hawai'i, 2018b). The current sustainable-yield estimate for the island of Lāna'i is 6 Mgal/d (State of Hawaii, 2018b), which is entirely from two aquifer systems (Windward and Leeward) in the central part of the island (fig. 1). Thus, projected demand is expected to exceed 60 percent of the estimated sustainable yield within 15 years. Available climate projections for mid-century and end-of-century conditions indicate that rainfall may decrease over much of Lāna'i (Elison Timm and others, 2015), including over areas where groundwater is most heavily developed. Projected increases in water demand coupled with projected decreases in rainfall suggest a need for proactive planning and water management. As part of its priorities and action plan (State of Hawai'i, 2018b), CWRM recognizes the need to improve recharge estimates to include the best available information on climate-change impacts and to integrate the best available information on the impacts of climate change on long-range water resources planning. Estimates of future groundwater recharge based on published climate projections for a mid-century time frame will enable CWRM to evaluate how groundwater availability may be affected by climate change over a water-resources planning horizon (20 to 30 years) and potentially adjust sustainable-yield values.

OBJECTIVES AND SCOPE

The overall objective of this study is to quantify (1) the distribution of groundwater recharge on Lāna'i for recent climate conditions (1978–2007), (2) the distribution of groundwater recharge for recent drought conditions (determined from the five consecutive years during 1978–2007 with the lowest island-wide rainfall), and (3) potential future changes in groundwater recharge associated with selected climate projections relative to recent conditions. A water-budget model will be used to estimate groundwater recharge for recent conditions (1978–2007), recent drought conditions, mid-century projected climate conditions (2041–71), and a range of end-of-century projected climate conditions. These groundwater-recharge estimates are needed to evaluate the potential effects of climate change on water availability and groundwater-dependent ecosystems. Estimates of future groundwater recharge will incorporate published climate projections for Lāna'i available at the time this study begins.

RELEVANCE AND BENEFITS

Groundwater recharge estimates that will result from this study are needed for the management of limited water resources in the State of Hawai'i. CWRM requires estimates of future groundwater recharge to evaluate how sustainable-yield values may change throughout the State and potentially affect water management. In addition, estimates of future groundwater recharge will (1) enhance understanding of where to prioritize watershed-management efforts and ecohydrology studies, (2) provide information needed to develop numerical groundwater models that will be useful for evaluating potential changes to groundwater systems and natural discharges, and (3) enable characterization of the relative impacts of climate change and land-use change on groundwater recharge. This study will provide the latest information needed for planning and management of groundwater resources and will enhance knowledge of the effects of climate change on groundwater availability and groundwater-dependent ecosystems in the State. This study is thus consistent with the USGS science directions (U.S. Geological Survey, 2007) related to (1) a water census of the United States; (2) climate variability and change; (3) understanding ecosystems and predicting ecosystem change.

This proposed study also addresses the USGS Water Mission Area priorities (Evenson and others, 2012) of (1) improving integrated science planning for water; (2) conducting integrated watershed assessment, research, and modeling; (3) delivering water data and analyses to the Nation; and (4) advancing ecological flow science. This proposed study also meets the USGS Water Mission Area goals priorities (Evenson and others, 2012) of (1) providing society the information it needs regarding the amount and quality of water in all components of the water cycle at high temporal and spatial resolution, nationwide; (2) advancing our understating of processes that determine water availability; (3) predicting changes in the quantity and quality of water resources in response to changing climate, population, land use, and management scenarios; and (4) delivering timely hydrologic data, analyses, and decision-support tools seamlessly across the Nation to support water-resource decisions.

APPROACH

A water-budget model of the plant root zone will be used to compute the spatial distribution of groundwater recharge for the island of Lāna'i for recent (1978–2007) conditions, 5-year drought conditions during 1978–2007, mid-century (2041–71) projected climate conditions, and end-of-century projected climate conditions using the best available datasets. For this study, a daily computation interval will be used in the water budget to avoid potential biases associated with coarser (monthly or annual) computation intervals. The water-budget model accounts for daily changes in soil moisture in the plant root-zone system related to water inputs (rainfall, fog interception, and irrigation) and outputs (runoff and evapotranspiration). The computation methods have been previously documented (Engott and others, 2017; Johnson and others, 2018; Izuka and others, 2018). The reader is referred to the cited references for details related to the water-budget computation approach that will be used in this proposed study.

Water-Budget Code

Previously published USGS water budgets for Hawai'i have used a geographic-information system (GIS) approach that discretizes the island using irregularly shaped subareas, each with uniform hydrologic properties (see, for example, Engott and others, 2017; Johnson and others, 2018; Izuka and others, 2018). For this study, consideration will be given to developing spatial recharge estimates using a grid-based approach (Westenbroek and others, 2018), in which the island is discretized using a regular grid. Use of the grid-based approach will enable incorporation of results in a web-based interface tool, which is being developed by the USGS in cooperation with the University of Hawai'i, for evaluating how groundwater recharge changes in response to land-cover and climate changes.

Land-Cover Conditions

To isolate the effects of climate change on groundwater recharge, the same land-cover conditions will be used to estimate groundwater recharge for recent (1978–2007) and future climate conditions for each island. The best available land-cover maps will be used and modified as appropriate to reflect recent conditions (for example, U.S. Geological Survey, 2016). Sources of water related to watermain leakage and septic systems may contribute to the water budget. Where the rates of water input related to watermain leakage and septic systems can be reasonably estimated, these sources will be incorporated in the water-budget model.

Soil and Vegetation Properties

Soil properties needed in the water-budget model will be based on published soil survey geographic (SSURGO) datasets from the Natural Resources Conservation Service (https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/). Vegetation properties, including root depth, canopy capacity, trunk-storage capacity, and evapotranspiration crop coefficient, will be based on published estimates (Engott and others, 2017; Johnson and others, 2018; Izuka and others, 2018) or critical new information that may become available prior to the start of this study.

Irrigation

Irrigation rates will be determined using supply-based estimates where data permit and demand-based estimates elsewhere. Methods used to estimate irrigation rates will be consistent with previously published methods (Engott and others, 2017; Johnson and others, 2018).

Runoff

Streamflow data from long-term, continuous-record streamflow-gaging stations are not available for Lāna‘i. Thus, published regression equations (Engott and others, 2017; Johnson and others, 2018; Izuka and others, 2018) developed from selected statewide data will be used in this study.

Recent Climate Conditions

Estimates of groundwater recharge for recent climate conditions will incorporate published rainfall for the period 1978–2007 (Giambelluca and others, 2013; Frazier and others, 2016) and best available reference evapotranspiration data for the State (Giambelluca and others, 2014). Fog interception may be present above an altitude of about 2,000 ft, within the cloud-forming zone on mountain slopes. Estimates of the rates and distributions of fog interception will be based on published methods (Engott and others, 2017; Johnson and others, 2018) that considers site-specific information as appropriate (Ekern, 1964; Juvik and others, 2011). Groundwater recharge estimated using the selected recent climate conditions will be used to provide a consistent baseline for comparison with recharge for drought and projected future conditions to evaluate recharge changes related to climate.

Annual rainfall on Lāna‘i during 1978–2007 (Giambelluca and others, 2013; Frazier and others, 2016) will be analyzed to identify the five driest consecutive years. These five years will be used to represent drought conditions for recent climate conditions. Groundwater recharge during the 5-year period will be estimated using the water-budget model.

Projected Climate Conditions

As part of ongoing USGS studies and a companion proposed USGS study, groundwater recharge for mid-century conditions and a range of end-of-century conditions (wetter and drier) (Zhang and others, 2016; Elison Timm and others, 2015) is being estimated for Kaua‘i, O‘ahu, Moloka‘i, Maui, and Hawai‘i. Methods used to incorporate projected climate information into the water-budget model have been developed for Maui as part of a separate USGS study (Alan Mair, U.S. Geological Survey, written commun., 2019). These methods are expected to be used for this proposed study as well.

As part of this study, groundwater recharge for mid-century conditions will be estimated for Lāna‘i. Currently, projected rainfall for mid-century conditions is available for RCP4.5 and RCP8.5 scenarios using statistical-downscaling methods (Elison Timm and others, 2015). If no other statewide projections for mid-century conditions are available at the time this study begins, the existing projected mid-century (2041–71) rainfall for the RCP8.5 scenario (Elison Timm and others, 2015) will be incorporated in this study. Projected rainfall for the RCP8.5 scenario would be selected over the RCP4.5 scenario to provide greater contrast (drier conditions) relative to recent conditions, which is consistent with “a precautionary and adaptive approach to water management to ensure the long-term protection of our water resources…” (State of Hawaii, chapter 1, p. 10).

Groundwater recharge for end-of-century conditions will be estimated for a range of projected climate conditions. Available end-of-century climate projections for Lāna‘i all indicate overall drying on the island (Zhang and others, 2016; Elison Timm and others, 2015). For this study, groundwater recharge will be estimated for the least and most severe published projected end-of-century drying climate conditions.

PRODUCTS

Results of this study will be documented in a USGS Scientific Investigations Report that will be made available to the public through the internet. In addition, digital spatial datasets of groundwater recharge for recent (1978–2007), drought, and projected future conditions will be published and made available to the public through the internet. Spatially distributed recharge results will be aggregated by aquifer system and recharge totals by aquifer system will be presented in tabular format in the report. This study will take 2.5 years to complete once initiated. CWRM staff will be kept informed of progress and findings through scheduled meetings and quarterly progress updates.

Table 1. Milestone dates for planned products.

Probable title	Product outlet	First draft	Review	Approval	Publication
Assessment of groundwater recharge for recent, drought, mid-century, and end-of-century climate conditions, Lāna'i, Hawai'i	USGS SIR	2/2021	05/2021	08/2021	11/2021
Recharge datasets for recent, drought, mid-century, and end-of-century climate conditions, Lāna'i, Hawai'i	ScienceBase	2/2021	05/2021	08/2021	11/2021

TIMELINE

The major tasks and associated timelines for this study are summarized in Table 2.

Table 2. Major study tasks and timelines by calendar year.

	2019				2020				2021			
Task	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
PHASE I												
Obtain and process datasets		X	X	X								
PHASE II												
Prepare input files				X	X	X	X					
Compute and analyze water budget					X	X	X	X				
Publication (datasets and report)												
Prepare draft								X	X			
Review										X		
Approval											X	
Publish on internet												X

BUDGET

This proposed 2.5-year study is estimated to cost $320,000 which will be cost shared by CWRM ($224,000) and USGS ($96,000). A cost breakdown is provided in Table 3. Labor includes salary and indirect costs for leave, facilities, and overhead assessments. Science support includes indirect costs for project management, technical services, and report processing fees. The budget for phase 1 is $50,000 and covers the project tasks outlined in Table 2 for a period of 6 months from June 1, 2019 to November 30, 2019. The budget for phase 2 is $270,000 and covers the project tasks outlined in Table 2 for a period of 24 months from December 1, 2019 to November 30, 2021. Progress letters summarizing status of the study will be provided on a quarterly basis.

Table 3. Project budget for the study.

Category	Phase 1 June 1, 2019- November 30, 2019	Phase 2 December 1, 2019- November 30, 2021	Total June 1, 2019- November 30, 2021
Labor	$ 44,800	$ 241,900	$ 286,700
Science Support	$ 5,200	$ 28,100	$ 33,300
Total	**$ 50,000**	**$ 270,000**	**$ 320,000**
CWRM	$ 40,000	$ 184,000	$ 224,000
USGS	$ 10,000	$ 86,000	$ 96,000

REFERENCES

Bassiouni, M., and Oki, D.S., 2013, Trends and shifts in streamflow in Hawai‘i, 1913–2008: Hydrological Processes, v. 27, no. 10, p. 1484–1500.

Chu, P.-S., and Chen, H., 2005, Interannual and interdecadal rainfall variations in the Hawaiian Islands: Journal of Climate, v. 18, p. 4796–4813.

Dorrance, W.H., and Morgan, F.S., 2000, Sugar islands, the 165-year story of sugar in Hawai‘i: Honolulu, Mutual Publishing, 259 p.

Ekern, P.C., 1964, Direct interception of cloud water on Lanaihale, Hawaii: Soil Science Society of America Proceedings, v. 28, no. 3, p. 419–421.

Elison Timm, O., 2017, Future warming rates over the Hawaiian Islands based on elevation-dependent-scaling factors: International Journal of Climatology, v. 37, p. 1093–1104, doi: 10.1002/joc.5065.

Elison Timm, O., Giambelluca, T.W., and Diaz, H.F., 2015, Statistical downscaling of rainfall changes in Hawai‘i based on the CMIP5 global model projections: Journal of Geophysical Research: Atmospheres, v. 120, no. 1, p. 92–112, doi: 10.1002/2014JD022059.

Engott, J.A., Johnson, A.G., Bassiouni, M., Izuka, S.K., and Rotzoll, K., 2017, Spatially distributed groundwater recharge for 2010 land cover estimated using a water-budget model for the Island of Oʻahu, Hawaiʻi (ver. 2.0, December 2017): U.S. Geological Survey Scientific Investigations Report 2015–5010, 49 p., https://doi.org/10.3133/sir20155010.

Evenson, E.J., Orndorff, R.C., Blome, C.D., Bohlke, J.K., Herschberger, P.K., Langenheim, V.E., McCabe, G.J., Morlock, S.E., Reeves, H.W., Verdin, J.P., Weyers, H.S., and Wood, T.M., 2012, Strategic directions for U.S. Geological Survey water science, 2012–2022—Observing, understanding, predicting, and delivering water science to the Nation: U.S. Geological Survey Open-File Report 2012–1066, 42 p., https://pubs.usgs.gov/of/2012/1066/.

Frazier, A.G., Giambelluca, T.W., Diaz, H.F., and Needham, H.L., 2016, Comparison of geostatistical approaches to spatially interpolate month-year rainfall for the Hawaiian Islands: International Journal of Climatology, v. 36, no. 3, p. 1459–1470, at http://dx.doi.org/10.1002/joc.4437.

Giambelluca, T.W., Chen, Q., Frazier, A.G., Price, J.P., Chen, Y.-L., Chu, P.-S., Eischeid, J.K., and Delparte, D.M., 2013, Online Rainfall Atlas of Hawaiʻi: Bulletin of the American Meteorological Society, v. 94, p. 313–316, doi: 10.1175/BAMS-D-11-00228.1, at http://rainfall.geography.hawaii.edu/.

Giambelluca, T.W., Diaz, H.F., and Luke, M.S.A., 2008, Secular temperature changes in Hawaii: Geophysical Research Letters, v. 35, p. L12702.

Giambelluca, T.W., Shuai, Xiufu, Barnes, M.L., Alliss, R.J., Longman, R.J., Miura, Tomoaki, Chen, Qi, Frazier, A.G., Mudd, R.G., Cuo, Lan, and Businger, A.D., 2014, Evapotranspiration of Hawaiʻi: Final report, submitted to U.S. Army Corps of Engineers–Honolulu District and Commission on Water Resource Management, State of Hawaiʻi, 178 p.

Gomes, A. 2017, Fresh ideas, tech billionare Larry Ellison wants to turn Lanai into an agricultural pioneer using high-tech greenhouses: Honolulu Star Advertiser, Sunday, August 6, 2017, p. A1, A10.

Hawkins, R.A., 2007, James D. Dole and the 1932 failure of the Hawaiian Pineapple Company: The Hawaiian Journal of History, v. 41, p. 149–170, accessed February 12, 2019, at https://evols.library.manoa.hawaii.edu/bitstream/10524/12232/1/HJH41_149-170.pdf.

Intergovernmental Panel on Climate Change, 2000, Special Report on Emissions Scenarios (SRES) (Nakicenovic, Nebojsa & Swart, Rob, Eds.): Cambridge University Press, Cambridge, United Kingdom, 570 p.

Intergovernmental Panel on Climate Change, 2013, Climate change 2013, the physical science basis, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P. M. Midgley, Eds.): Cambridge University Press, Cambridge, UK and New York, USA.

Izuka, S.K., Engott, J.A., Rotzoll, K., Bassiouni, M., Johnson, A.G., Miller, L.D., and Mair, A., 2018, Volcanic aquifers of Hawaiʻi—Hydrogeology, water budgets, and conceptual models (ver. 2.0, March 2018): U.S. Geological Survey Scientific Investigations Report 2015-5164, 158 p., https://doi.org/10.3133/sir20155164.

Juvik, J.O., Delay, J.K., Kinney, K.M., and Hansen, E.W., 2011, A 50th anniversary reassessment of the seminal "Lānaʻi fog drip study" in Hawaiʻi: Hydrological Processes, v. 25, p. 402–410.

Juvik, S.P., and Juvik, J.O., eds., 1998, Atlas of Hawaiʻi: University of Hawaiʻi Press, Honolulu, 33 p.

Johnson, A.G., Engott, J.A., Bassiouni, M., and Rotzoll, K., 2018, Spatially distributed groundwater recharge estimated using a water-budget model for the Island of Maui, Hawai`i, 1978–2007 (ver. 2.0, February 2018): U.S. Geological Survey Scientific Investigations Report 2014–5168, 53 p., https://doi.org/10.3133/sir20145168.

Langenheim, V.A.M., and Clague, D.A., 1987, The Hawaiian-Emperor volcanic chain, part II, stratigraphic framework of volcanic rocks of the Hawaiian Islands, chap. 1 of Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 55–84.

Moore, J.G., Clague, D.A., Holcomb, R.T., Lipman, P.W., Normark, W.R., and Torresan, M.E., 1989, Prodigious submarine landslides on the Hawaiian Ridge: Journal of Geophysical Research, v. 94, no. B12, p. 17,465–17,484.

Oki, D.S., 2003, Surface water in Hawai'i: U.S. Geological Survey Fact Sheet 045–03.

Oki, D.S., 2004, Trends in streamflow characteristics at long-term gaging stations, Hawai'i: U.S. Geological Survey Scientific Investigations Report 2004–5080, 116 p.

Schroeder, T.A., 1993, Climate controls, chap. 2 *of* Sanderson, M. ed., Prevailing trade winds, weather and climate in Hawai'i: Honolulu, University of Hawai'i Press, p. 12–36.

Sherrod, D.R., Sinton, J.M., Watkins, S.E., and Brunt, K.M., 2007, Geologic map of the State of Hawai'i: U.S. Geological Survey Open-File Report 2007–1089, 83 p.

State of Hawai'i, 2018a, The State of Hawaii data book, a statistical abstract, 2017, 50th edition, November 2018 update, Hawai'i Department of Business, Economic Development, and Tourism, accessed February 12, 2019, at http://dbedt.hawaii.gov/economic/databook/db2017/.

State of Hawai'i, 2018b, Water resource protection plan, 2019 update: State of Hawai'i, Commission on Water Resource Management, variously paged, accessed January 29, 2019, at https://dlnr.hawaii.gov/cwrm/planning/hiwaterplan/wrpp/.

Stearns, H.T., 1940, Geology and ground-water resources of the islands of Lanai and Kahoolawe, Hawaii: Hawai'i Division of Hydrography Bulletin 6, 177 p.

The Pineapple Growers Association of Hawaii, 1973, Pineapple fact book, Hawaii, 1973, Honolulu, 24 p.

Timm, O., and Diaz, H.F., 2009, Synoptic-statistical approach to regional downscaling of IPCC twenty-first-century climate projections: seasonal rainfall over the Hawaiian Islands: Journal of Climate, v. 22, p. 4261–4280, doi: 10.1175/2009JCLI2833.1.

U.S. Geological Survey, 2007, Facing tomorrow's challenges—U.S. Geological Survey science in the decade 2007–2017: U.S. Geological Survey Circular 1309, x + 70 p., https://pubs.usgs.gov/circ/2007/1309/.

U.S. Geological Survey, 2016, LANDFIRE existing vegetation type, 2014 (LF_1.4.0): Earth Resources Observation and Science Center, U.S. Geological Survey, accessed February 13, 2019, at https://landfire.cr.usgs.gov/viewer.

Wang, Y., Chunxi, Z., Axel, L., and Kevin, H., 2016, Hawaii regional climate model simulations (HRCM): Asia-Pacific Data-Research Center, International Pacific Research Center, accessed August 3, 2016, at http://apdrc.soest.hawaii.edu/projects/HRCM/.

Westenbroek, S.M., Engott, J.A., Kelson, V.A., and Hunt, R.J., 2018, SWB Version 2.0—A Soil-Water-Balance code for estimating net infiltration and other water-budget components: U.S. Geological Survey Techniques and Methods, book 6, chap. A59, 118 p., https://doi.org/10.3133/tm6A59.

Zhang, C., Wang, Y., Hamilton, K., and Lauer, A., 2016, Dynamical downscaling of the climate for the Hawaiian Islands, part II, projection for the late twenty-first century: Journal of Climate, v. 29, no. 23, p. 8333–8354, doi: 10.1175/JCLI-D-16-0038.1.

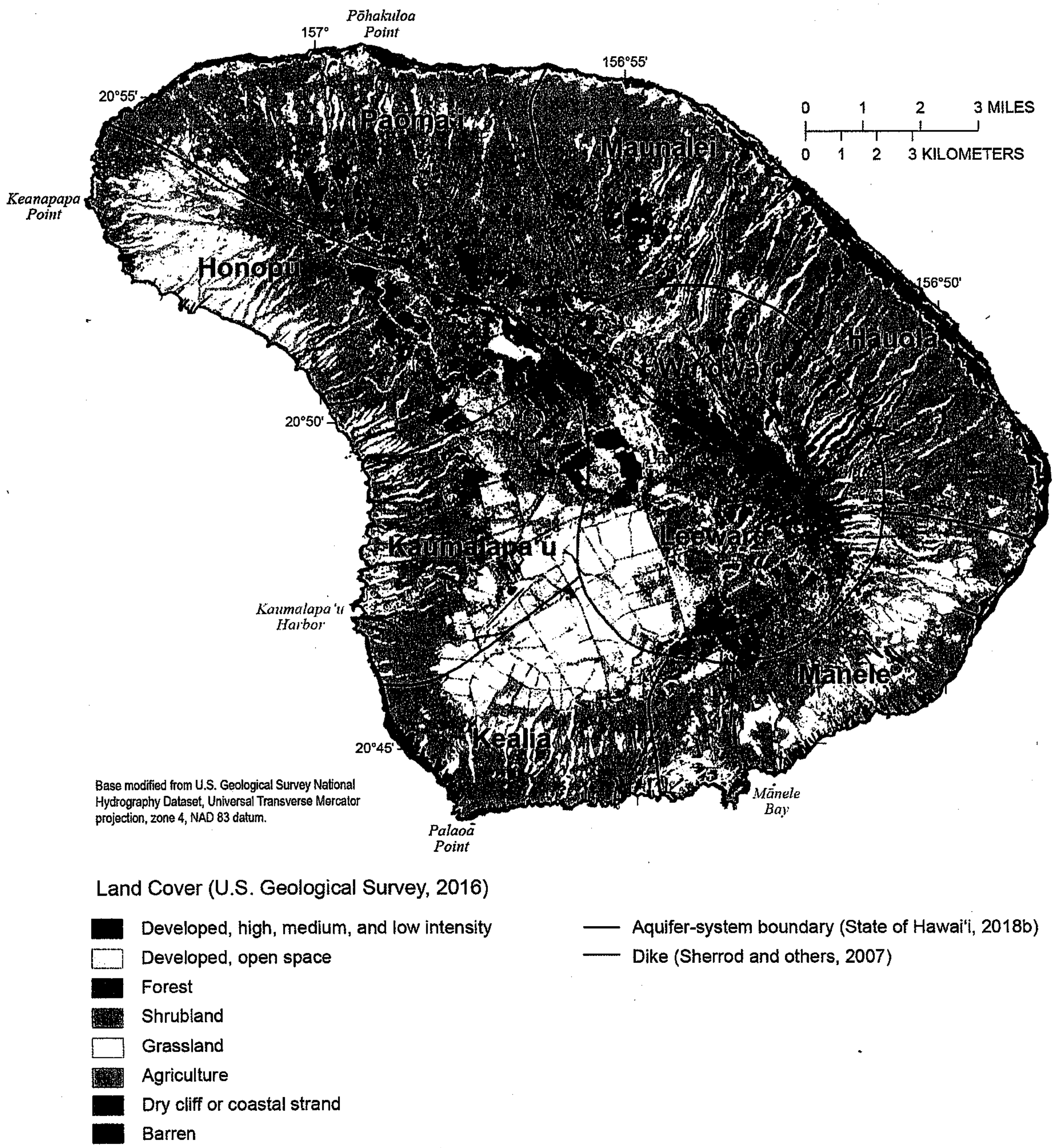

Figure 1. Aquifer systems defined by the Hawai'i Commission on Water Resource Management and generalized land cover on the island of Lāna'i, Hawai'i.